NASA-CR-202715

# TELESCOPE SCIENTIST ON THE ADVANCED X-RAY ASTROPHYSICS OBSERVATORY

The articles appended here and published in the *AXAF News* summarize the work completed on this project during the referenced period.

NASA Grant NAG8-792

Semiannual Reports No. 1–8

For the Periods 13 January 1990 - 12 July 1990, 13 July 1990 - 1 January 12 1991, 13 January 1991 - 12 July 1991, 13 July 1991 - 12 January 1992, 13 January 1992 - 12 July 1992, 13 July 1992 - 12 January 1993, 13 January 1993 - 12 July 1993, 13 July 1993 - 12 January 1994

Annual Reports No. 1 and 2

For the Periods 13 January 1994 - 12 January 1995, 13 January 1995 - 12 January 1996

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November 1996

Prepared for:

National Aeronautics and Space Administration
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The Smithsonian Astrophysical Observatory
is a member of the
Harvard-Smithsonian Center for Astrophysics

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The AXAF-I High Resolution Mirror Assembly (HRMA) is one of the major technical challenges and longest lead-time elements of the AXAF program. Currently we are in the production phase of the mirror elements, and have completed much of the equipment required for the final HRMA alignment and assembly.

## Optical Design of AXAF-I

Most readers will be familiar with the optical design, but a brief description may be helpful to some. The original design included six concentric mirror pairs, each pair consisting of a paraboloid and a hyperboloid. Two pairs were removed from the design as part of the 1992 restructuring of AXAF; we continue to use the original nomenclature to avoid confusion in the documents, so the four pairs of the present design are numbered 1, 3, 4, and 6, with pair 1 being the largest and pair 6 the smallest. The paraboloid and hyperboloid of pair 1 are called P1 and H1 respectively, and similarly for the other elements. The individual shells resemble shallow cones; all elements are 838.2 mm long, and the diameters at the pair intersections are approximately 1199 mm, 966 mm, 853 mm, and 634 mm for pairs 1, 3, 4, and 6 respectively. The deviation of any individual mirror element from a cone actually is quite small, about 36 $\mu$m for H1, and less for the other elements. The paraboloids have a common focus which is located approximately 20 meters behind the center of the HRMA; the two foci of each hyperboloid are the (common) focus of its associated paraboloid and the system focus, the latter being approximately 10 meters behind the HRMA center. The design results in the on-axis rays making approximately equal grazing angles with both surfaces because this choice maximizes the throughput for a given area of polished glass; the typical grazing angles are 52, 42, 37, and 27 arcminutes for pairs 1, 3, 4, and 6 respectively. This geometry and the reflection properties of the Iridium coating result in HRMA effective areas of about 780, 445, 465 and 265 $cm^2$ at 1, 3, 4, and 6.4 keV respectively (after allowance for obscuration by mechanical supports). The total polished area is about that of a five meter diameter normal incidence mirror.

Composition

The mirror elements are made of Zerodur, a glass ceramic made by Schott in Germany. The wall thicknesses are about 23.6, 18.3, 16.5, and 15.9 mm for pairs 1, 3, 4, and 6, respectively, providing similar stiffnesses against oval distortions during fabrication and metrology. These thin walls would result in unacceptable mirror distortions as a result of self-weight induced deflections if the mirror elements were not supported carefully. The flight mirror elements are supported at their centers with graphite composite sleeves; this arrangement reduces the performance destructive mode in which the mirror ends become oval with the major axis at the small end being perpendicular to the major axis at the large end. The composite sleeves are supported by an aluminum center aperture plate. The Zerodur and composite materials were selected in part for their low coefficients of thermal expansion (the composite sleeves isolate the mirror elements from the effects of the aluminum center aperture plate), which allows achievable tolerances on temperatures during metrology, alignment, and operation.

Element Fabrication

The mirror element fabrication is a major activity being performed at Hughes Danbury Optical Systems, Inc. (HDOS) in Danbury, CT (Fig. 3). The process is fairly conventional, but complicated by the tight tolerances and the flexibility of the elements. The typical process cycle consists of metrology to determine the current shape of the glass, data analysis, run planning, and corrective material removal. The final cycle is followed by acceptance metrology, which also is used to optimize the initial alignment and for performance prediction.

The major instruments used during metrology are the CIDS (circularity and inner diameter station) and the PMS (precision metrology station). The CIDS, as its name implies, is used to determine circularity and the inner diameters. The PMS is used to measure along a meridian; thus, between the two instruments we essentially measure both the 'hoops' and 'staves' of the barrel, and can map the entire surface.

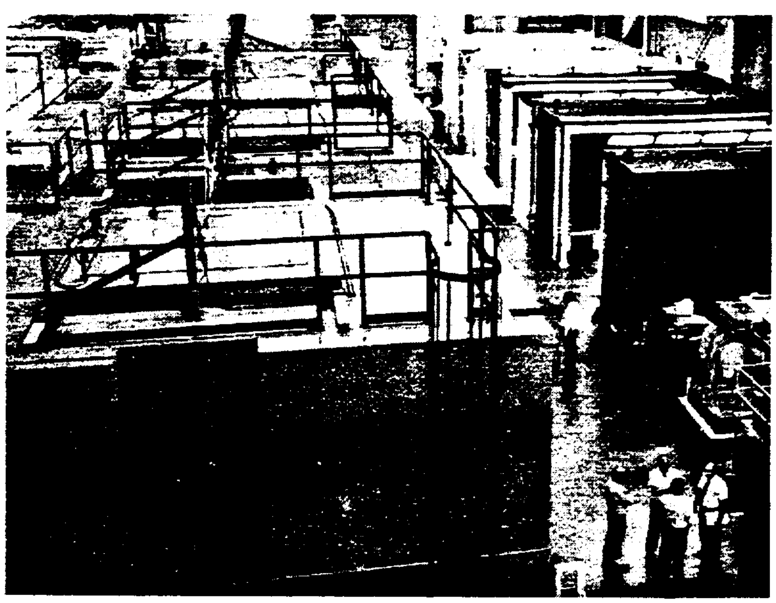

Figure 3. Mirror fabrication room at Hughes Danbury Optical Systems, Inc. The Precision Metrology Station is housed in the enclosure in the foreground. [Photo courtesy of Hughes Danbury Optical Systems, Inc]

The CIDS detectors are air bearing supported, inductively loaded probes; two opposing probes are carried on each of two arms which are located near the top and bottom of the glass, thus making simultaneous measurements 180° apart at both stations. One end of a probe is a small sphere which makes contact with the glass, and the other end is a mirror normal to the probe axis. The separation between a fixed optical reference cube and the mirror on the back of the probe is measured with a laser interferometer. This entire assembly then is rotated on a precision air bearing to determine the circularity at axial stations near the edges. The opposing probes provide the data required to correct for errors in the bearing. The inner diameters are measured by retracting the probes and then moving the arms axially so that calibrated Zerodur reference bars can be measured. Checks against systematic errors include reversing the glass top to bottom so that the measurement of the difference in radii, or equivalently the average axial slope, will be insensitive to errors in the calibration of the reference bars; fortunately, we are not very sensitive to errors in the absolute diameters. The glass also is rotated on the CIDS so that any errors azimuthally fixed with the instrument can be detected and compensated. The elapsed time for a set of CIDS measurements is about three days, depending on whether or not the glass is inverted, etc.

The PMS is used to measure interferometrically the separation between a carefully calibrated reference cylinder (which is called a toroid for historical reasons). One azimuthal position is measured a number of times, typically 10, but as many as 40 for final acceptance. The mirror element then is rotated azimuthally and the process repeated. Typically 144, 288, or 576 meridians are measured, depending upon the stage of the polishing process. Two types of tests for systematic errors are performed. The element can be displaced axially by small amounts, resulting in sensitivity to errors higher than second order as long as they are not periodic with a period equal to an integral divisor of the displacement; this is called a shear test, and can be performed with an accuracy comparable to the tolerances. The mirror also can be inverted, providing sensitivity to errors which are odd functions of the axial coordinate. These two types of check provide sanity measurements for all PMS parameters except for the sagittal depth, or 'axial sag'. The sanity checks for axial sag include varying the axial stations measured with the CIDS, and making a direct comparison with two lower resolution mechanical profilometers which are used in the earlier stages of the fabrication process; the accuracies of these cross checks are comparable to the requirements. The elapsed time for a set of PMS measurements is about four days, again depending upon how extensive a data set is required.

The mirror must be supported carefully during CIDS and PMS measurements; this is accomplished using the precision metrology mount (PMM). The mirrors typically are supported at three 'hard' points, which determine position kinematically, and 15 'soft' points, in which a measured support force is applied, but position is not constrained. Tolerances on these off loading forces are of order 0.01 pounds, which may be compared to the approximately 500 pounds weight of the largest mirror elements. The PMM introduces distortions which must be calculated and removed from the data. The support induced distortions have scale lengths short compared to the length of the optical elements, and so the accuracy of the calculations can be verified by demanding consistency between data taken with the mirror in its normal and inverted orientations. This also provides a check on the PMM support force tolerance analysis.

Finally, after the last cycles, the microroughness is sampled using a slightly modified WYKO Corporation instrument on a mount which allows access to the inside of the optical elements.

The data analysis and run planning activity consists of reducing the data to determine the surface errors followed by tool selection to optimize the reduction of these errors. A run tape for each tool is generated; this essentially adjusts the local dwell times so that the convolution of the tool path and dwell times with the selected tool removal profile is proportional to the local errors. Typically of order 600 megabytes of raw data are processed for each polishing cycle of each element.

<u>Final Polishing</u>

Finally, the optical element is placed on a computer-controlled polishing machine (Fig. 4), and tools of different sizes are used with their associated run files to reduce the surface errors. These small tools are not effective in reducing errors with scale sizes smaller than their own dimensions, but fortunately such small-scale errors can be attacked efficiently with large smoothing laps, and these are used to reduce mid and high frequency surface errors. Typical polishing cycle times are of order two or three weeks, so the total cycle time is about a month. An optic now requires about four grinding cycles and seven polishing cycles to reach an acceptable tolerance.

This activity occupies an area somewhat over 2000 square meters, or about $\frac{2}{3}$ the size of a football field; the metrology is performed in temperature controlled 'blue boxes' which are about seven by eight meters by five meters high. The seemingly simple problems of just handling the glass, moving it from one place to another, changing from the constraining support hardware used for polishing to the strain-free PMM support used during measurement, etc., all require careful planning, auxiliary equipment, and time.

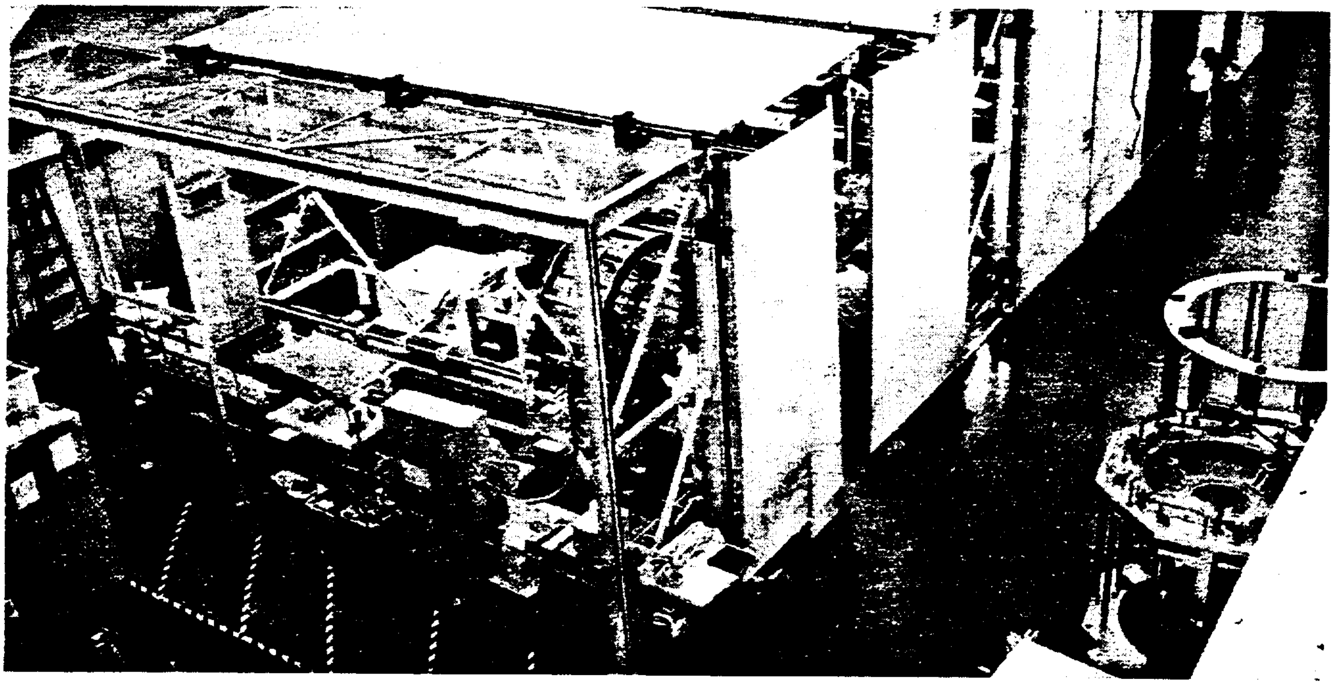

Figure 4. The largest paraboloid is shown in the automatic grinding and polishing machine at Hughes Danbury Optical Systems, Inc. The tent-like structures within the building help to provide humidity control. [Photo courtesy of Hughes Danbury Optical Systems, Inc]

Typically, greater difficulties are experienced near boundaries in the polishing process, and our original plan was to polish mirror elements about 75 mm overlength at each end, and then remove the excess material. We knew that residual stresses smaller than our ability to measure could introduce significant distortions, but we hoped that the symmetry of the annealing process at Schott would result in benign internal stresses. P1 and H1 were polished as a process demonstration, and tested as the first verification engineering test article (VETA-1) before this extra length was removed. The ends were removed after the successful X-ray demonstration tests ($\sim$ 0.2 arc seconds FWHM), and unfortunately unacceptable distortions were found to be introduced. We then changed the plan to correct P1 and H1, and to cut the other optical elements while the residual errors remained larger than the expected end cut deformations. So far four of the six remaining elements have been cut; of the three which have been measured, two showed little distortion, whereas the third showed distortions which would be unacceptable. The result of cutting early will be a slight degradation of the outer $\sim$ 10% of the mirror elements.

The final polishing cycle on P1 has just begun, and should be complete by the end of June. Final metrology, shipping, etc., should result in this mirror element being delivered by mid August. All mirror elements should be complete by May, 1995.

Alignment and Assembly

P1 and H1 will be delivered to the Eastman Kodak Corporation (EKC) for alignment and assembly as part of VETA-2. EKC will use these elements to check the alignment equipment and for mechanical tests. Following these tests, all mirror elements will be shipped to Optical Coating Laboratories, Inc. (OCLI) where the final cleaning and coating (with sputtered Iridium) will take place. OCLI first will verify the sputtering geometry on test samples which duplicate the required geometry for the optical elements. The final coating of the optical element (and witness samples) will be performed after satisfactory preliminary qualification runs are obtained. The mirror elements then will be shipped back to EKC for final alignment and assembly.

The final alignment and assembly at EKC will be performed in a vertical tower which is inside a class 100 clean area. The mirror elements, composite support sleeves, and aluminum center aperture plate all must be supported in a strain free manner. The mirror elements will be positioned above an optical flat located at the bottom of the assembly tower. The optical flat will be leveled to gravity, and the optical reference assembly mounted on the center aperture plate will be made parallel to the optical flat. The inner paraboloid (P6) then will be mounted so that its axis of symmetry is normal to the optical flat. The optical alignment sensor used for this purpose illuminates the paraboloid from near its focus; light passes through the paraboloid, reflects from the flat, and returns to a quad cell detector near the paraboloid focus. The software does a fourier decomposition of the centroid coordinates as a function of the azimuthal angle illuminated. The paraboloid is aligned normal to the flat when the centroid of the returned light does not show a $2\theta$ dependence upon the azimuth angle ($\theta$). The paraboloid focus is determined by finding the point where the centroid does not show a $1\theta$ dependence upon azimuth angle; proper axial and lateral alignment is achieved when the paraboloid focus is coincident with the center of a sphere which is part of the optical reference assembly mounted on the center aperture plate. This technique was developed on a technology development program, and shown to be sensitive to alignment errors of less than 0.02 arc seconds. The next smaller paraboloid (P4) then is added and aligned so that it is co-axial with P6 and the two paraboloid foci are coincident. The paraboloid focal lengths are about twice the system focal lengths, and this extra length is accommodated by fold flats. These fold flats then are removed and the first hyperboloid (H6) is added. The alignment is similar to that of the paraboloids; a $2\theta$ azimuthal dependence of the image centroid indicates that the hyperboloid focus is displaced laterally from that of the associated paraboloid. The position of the system focus can be adjusted laterally without any loss of resolution by rotating the hyperboloid about the common focus it shares with the associated paraboloid; the position of the system focus can be adjusted axially with small loss of resolution by displacing the hyperboloid axially. The position of H6 is adjusted to yield a coma-free (no $2\theta$ centroid dependence) image which is coincident with the center of a second sphere on the optical reference assembly. The next paraboloid (P3) then will be aligned so that its focus is coincident with that of P4; then H4 will be added so that its focus is coincident with that of H6, and so forth through P1, H3, and H1.

The mirror then will be shipped to the NASA Marshall Space Flight Center for final X-ray calibration, where the X-ray performance will be determined and compared with the expected results based upon the metrology data and the calculated degradation from gravity, finite source distance, detector resolution, and so forth. We had excellent agreement for the only previous mirror for which metrology adequate for this task existed, and we hope no surprises will be found.

– Leon Van Speybroeck

## Reflectivity Verification of the Coatings

The successful coating of the first two flight optics (P6 and H6) has just been completed, so it is an appropriate time to give a brief update on what has been happening.

Many readers may not be aware of the Process Selection Study (SAO report: SAO-AXAF-DR-92-016 by Pat Slane) which was carried out a few years ago under the recommendation of a coating working group comprised of members from TRW, the MSFC Project Office, MSFC Project Science, and the SAO Mission Support Team (MST). This study gathered information needed for the selection of materials, vendor, coating techniques, etc., for the coating of the AXAF optics. Based on the study, DC magnetron sputtering was recommended to be used as the coating technique, and iridium was chosen as the coating material. Also, at this time, Optical Coating Laboratories Incorporated (OCLI) of Santa Rosa, CA was chosen as the coating vendor by TRW via competitive procurement. The coating process includes a chromium undercoat which is first sputtered onto the optical surface to insure the adherence of the iridium layer which follows. The nominal thickness of the layers is 100Å of chromium and 350Å of iridium.

Based on the data gathered during the coating process selection study, a minimum performance criterion for the X-ray reflectivity of the coatings was specified to be used as an evaluation tool. The SAO/MST reflectivity laboratory in Cambridge is a facility dedicated to the AXAF program to provide quick turnaround reflectivity measurements for this evaluation. SAO/MST has been working with TRW, MSFC, and OCLI to provide the X-ray reflectivity measurements of the sample coatings.

The coating program with OCLI, which began in June of 1993, has three main phases: Scaleup, Validation, and Production. The activities during the Scaleup phase included the building and testing of the chamber in which the flight optics are coated. This phase also included several test runs to coat sample substrates in each of the mirror geometries (P6, H6, P4, etc). These coatings were then characterized to provide data to set the correct coating parameters for each geometry. This was completed in February 1995.

The Validation phase of the coating program (completed in April 1995) was used to show the reproduceability of coating parameters and coatings in each of the geometries.

The Production phase, which is underway now, denotes the period of time dedicated to the coating of the flight optics. This phase of the coating program began in June 1995, and approximately one flight optic per month is being coated until expected completion in February 1996.

During the production phase, a qualification coating run takes place several days prior to the coating of each optic. During the qualification run, several substrates ($6'' \times 2'' \times 1''$) are coated to give us a representative sampling of the coating geometry for each optic. These samples are measured at SAO to check that the coating meets the requirements and to check for linear and azimuthal coating uniformity. Within 48 hours of receiving the qualification samples, SAO/MST must verify that the coatings meet spec before OCLI can proceed with the coating of the flight optic. Along with the coating of the flight optic, six witness samples are coated and sent to SAO. These samples are then analyzed in the same way as the qualification samples.

Figure 1 shows X-ray reflectivity data from one of the coated witness samples from the H6 coating run. These data were taken with an 8.03 keV X-ray source, and one can see that the critical grazing angle for this energy occurs near 34 arcmin. A measure of the reflectivity near the critical angle is a sensitive probe of the density of the coatings, and a measurement of reflectivity below the critical angle provides information on the density gradients near the surface. For these reasons, the requirements were chosen such that the reflectivity be $\geq 82\%$ at 20 arcmin grazing angle and $\geq 50\%$ at 34 arcmin (at 8.03 keV) for the coatings to be acceptable (memo from Steve O'Dell to Steve Hixson, 11 June 1992).

Six of the flight optics have now been received at OCLI. The remaining two, P1 and H1, are scheduled to be shipped from Eastman Kodak Corporation (EKC) to OCLI in August '95. The order of coating is: P6, H6, P4, H4, P3, H3, P1, H1. As the optics are coated, they will be shipped in pairs to EKC for assembly, which is scheduled to begin in October '95.

Several dozen samples were characterized during the scaleup and validation phases of the program. The reflectivity of the coatings to date has generally exceeded specification, with only three cases of subpar reflectivity which was traced to improper cleaning of the substrate. The success of this phase is due to the cooperation and collaboration of OCLI, MSFC, TRW and SAO. In particular, we are fortunate to have a dedicated team of people at OCLI, headed by Jerry Johnston, the program manager, and Bob Hahn, OCLI's chief engineer for this project. OCLI is under subcontract to TRW, the spacecraft prime contractor, and much credit goes to Beth Barinek, the technical TRW contract manager, for her ability to keep the program running smoothly and for keeping the momentum in the forward direction!

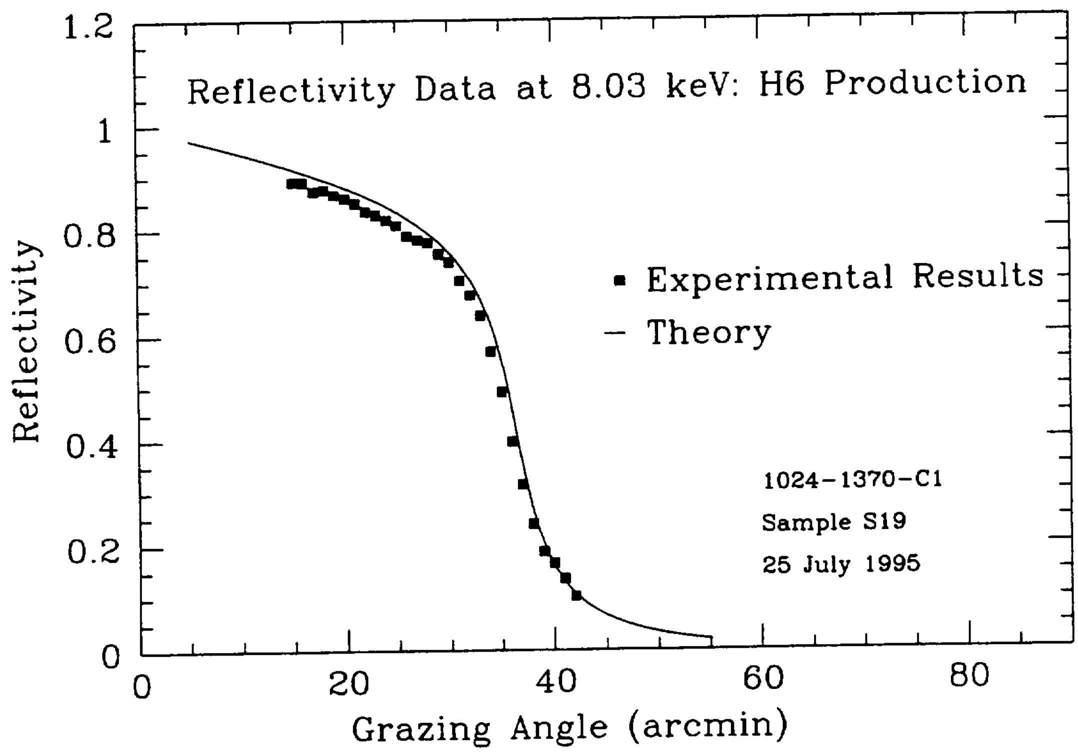


Figure 1. X-ray reflectivity as a function of grazing angle. Solid line is theoretical data for iridium and squares are experimental data for a sample from the production run for the smallest of the iridium-coated hyperboloid mirrors (H6). The X-ray energy is 8.03 keV.

Synchrotron Measurements

A number of the qualification and production witness samples are being set aside for precise reflectivity measurements at the Brookhaven National Laboratory (BNL) synchrotron. Time has been planned at BNL over the next four years to provide detailed measurements of reflectivity as a function of energy. These measurements will be used to determine the effective optical constants of the iridium and the true thicknesses of the sputtered layers. This program will be the subject of a future newsletter article.

– Suzanne Romaine